# Radio-optical outliers – a case study with ICRF2 and SDSS

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*QSO Astrophysics, Fundamental physics, and Astrometric Cosmology in the Gaia era*
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# Outline of the talk

**Direct link between the best radio and optical reference frames**
*astrometric and astrophysical importance*

**Are the common objects really coincident?**
*no Gaia yet – a case study with identifying ICRF2 sources in SDSS*

**How accurate is the SDSS astrometry in general?**
*Data Releases 7 & 8*

**Individual objects that are significantly non-coincident**
*how many and why?*

# Radio–optical link

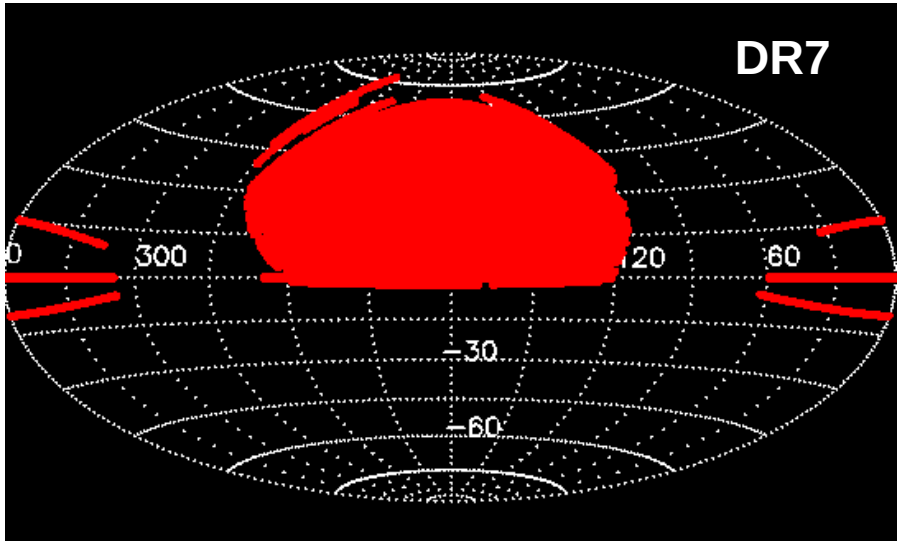
**Radio reference frame: based on VLBI positions of compact extragalactic radio sources (active galactic nuclei)**
*ICRF2 – Fey , Gordon & Jacobs (eds.) 2009*

**The quasars are too faint in optical**
*with the current catalogues, the radio-optical link is possible only indirectly, using a couple of radio-emitting stars*
*problems: quite few of them; proper motion inaccuracies deteriorate the quality with time*

**Gaia: a direct alignment of the reference frames – for the first time**
*~half a million quasars with a limiting magnitude of $m_V$~20*
*thousands of "good" bright sources will define an accurate frame*
*common Gaia-VLBI quasars → direct link*

**Are the optical and radio positions identical?**
*not necessarily; the real question is how different they are*

# While waiting for Gaia...




**Sloan Digital Sky Survey (SDSS)**
Data Release 7 (DR7)
**`cas.sdss.org/dr7`**

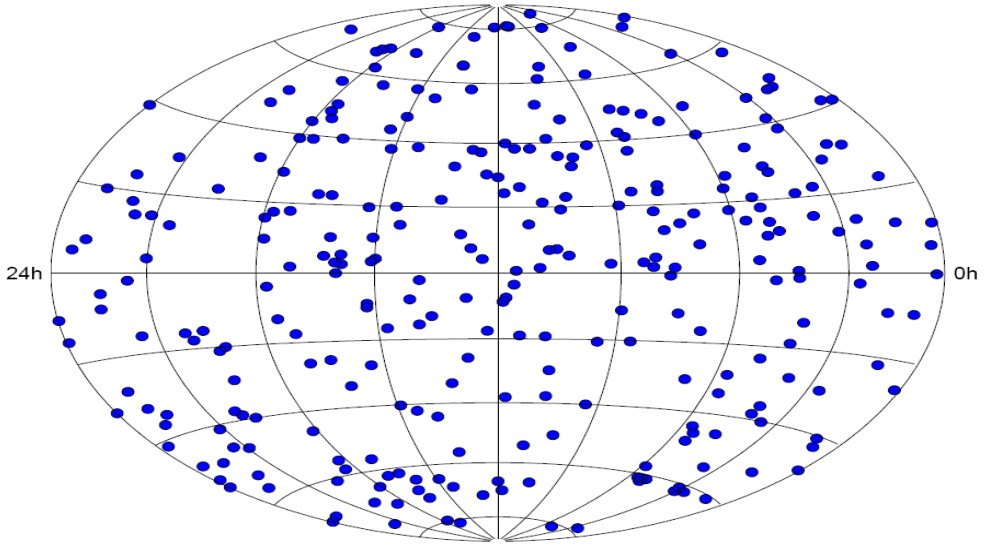
Data Release 8 (DR8)
**`skyserver.sdss3.org/dr8`**

*coverage: over 1/3 of the sky*
*magnitude limit: ~22$^{m}$*

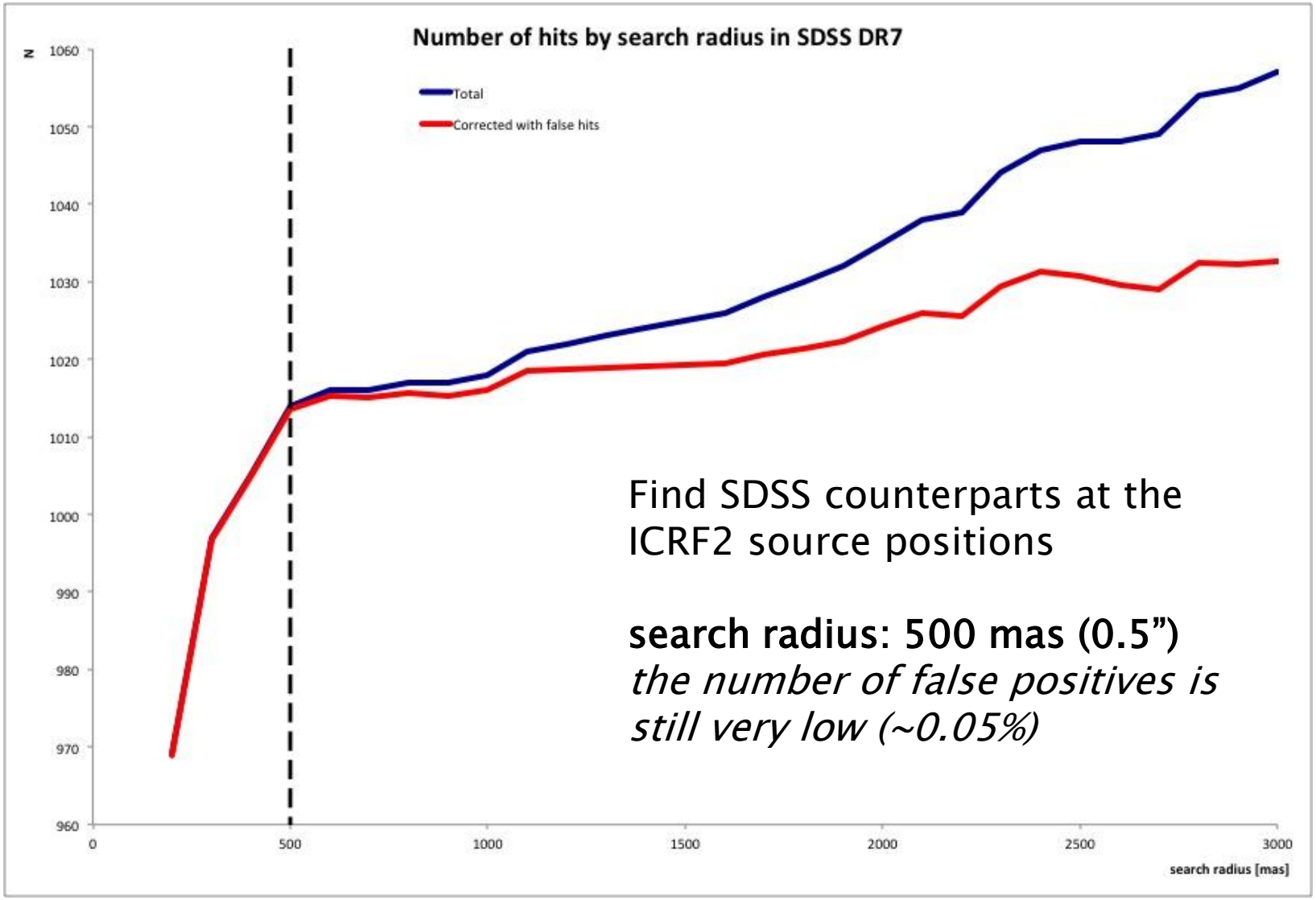
2nd realization of the
**International Celestial Reference Frame (ICRF2)**

IERS Technical Note 35

*295 defining sources, 3414 objects in total*



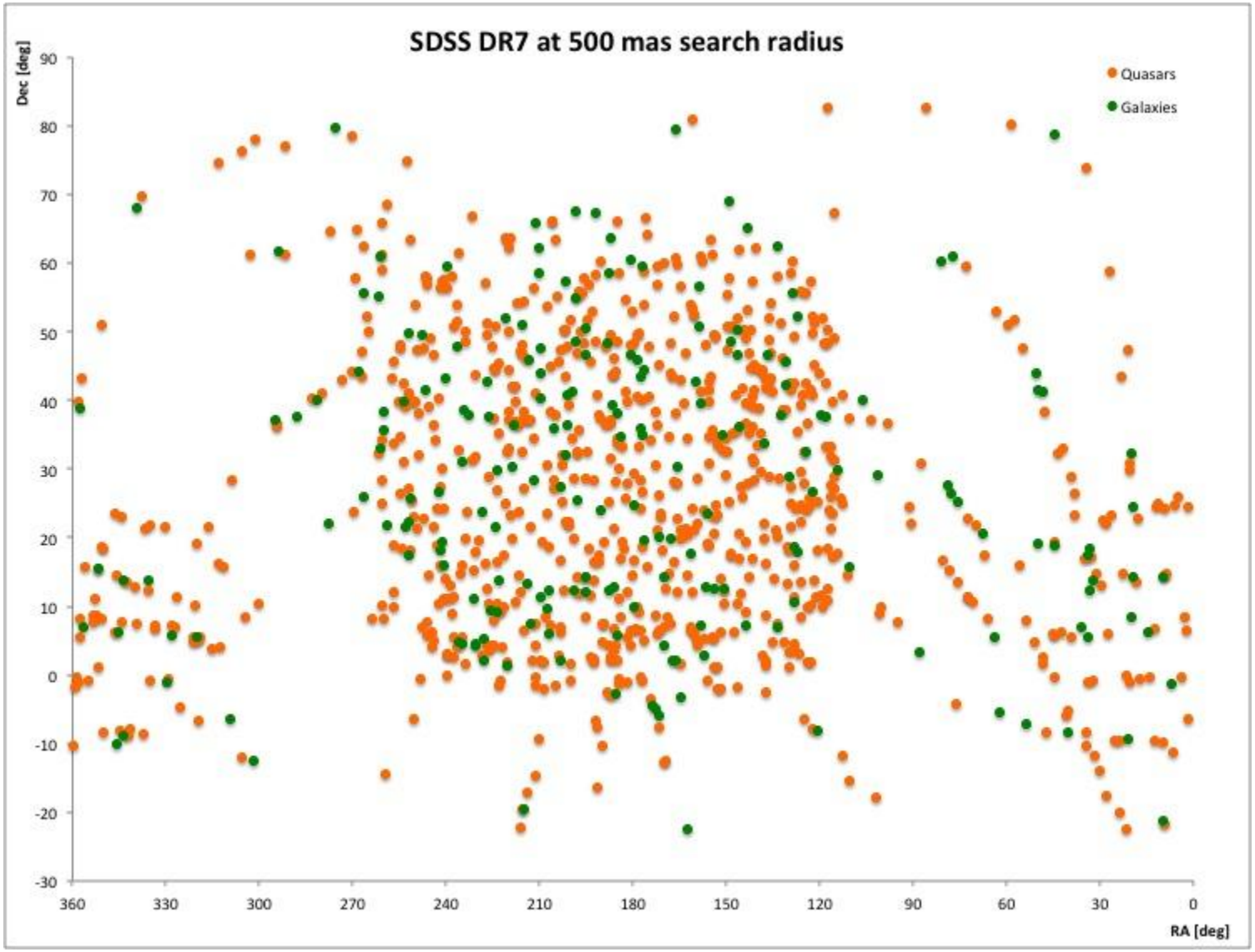
# ICRF2–SDSS cross-identifications



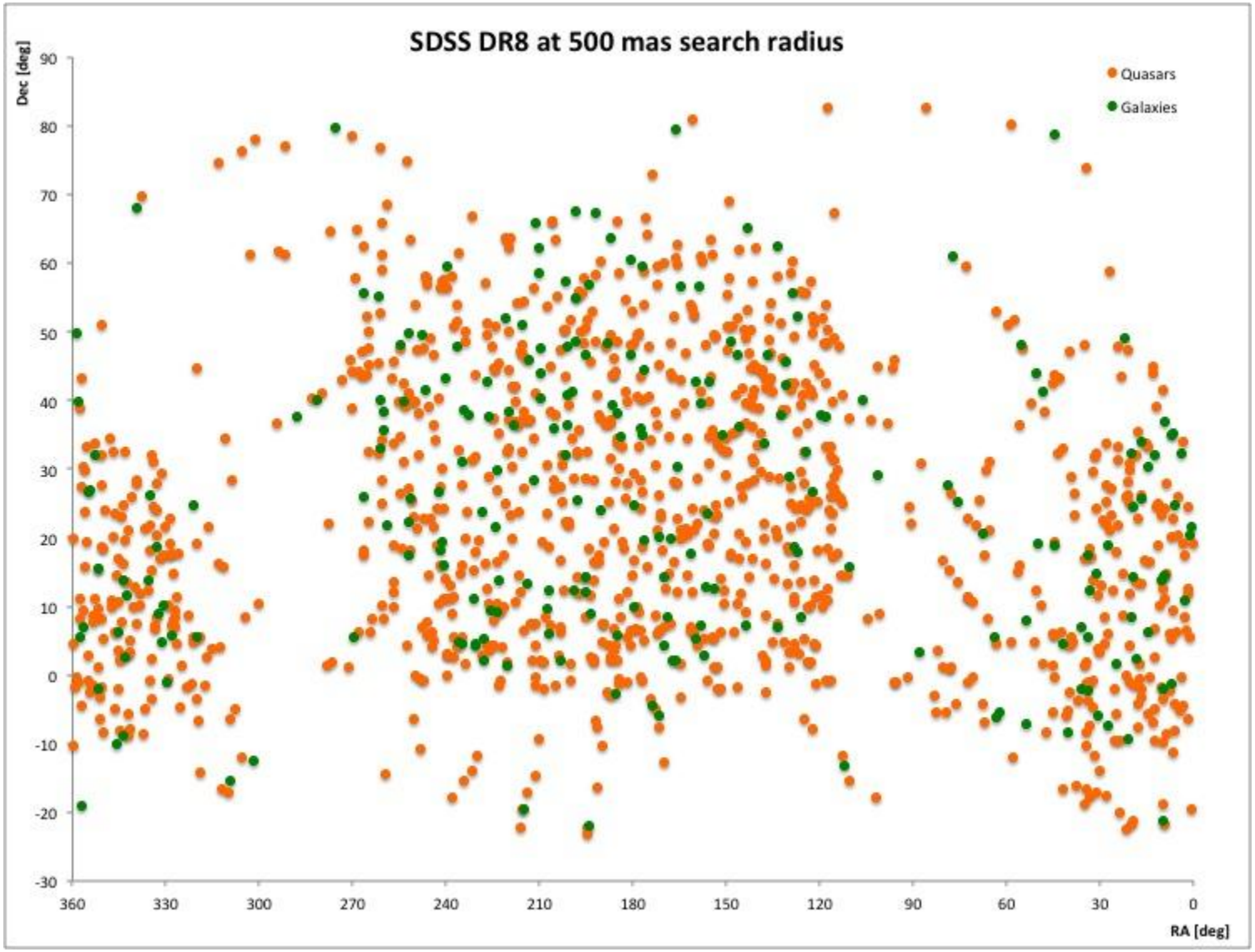

Find SDSS counterparts at the ICRF2 source positions

**search radius: 500 mas (0.5")**
*the number of false positives is still very low (~0.05%)*

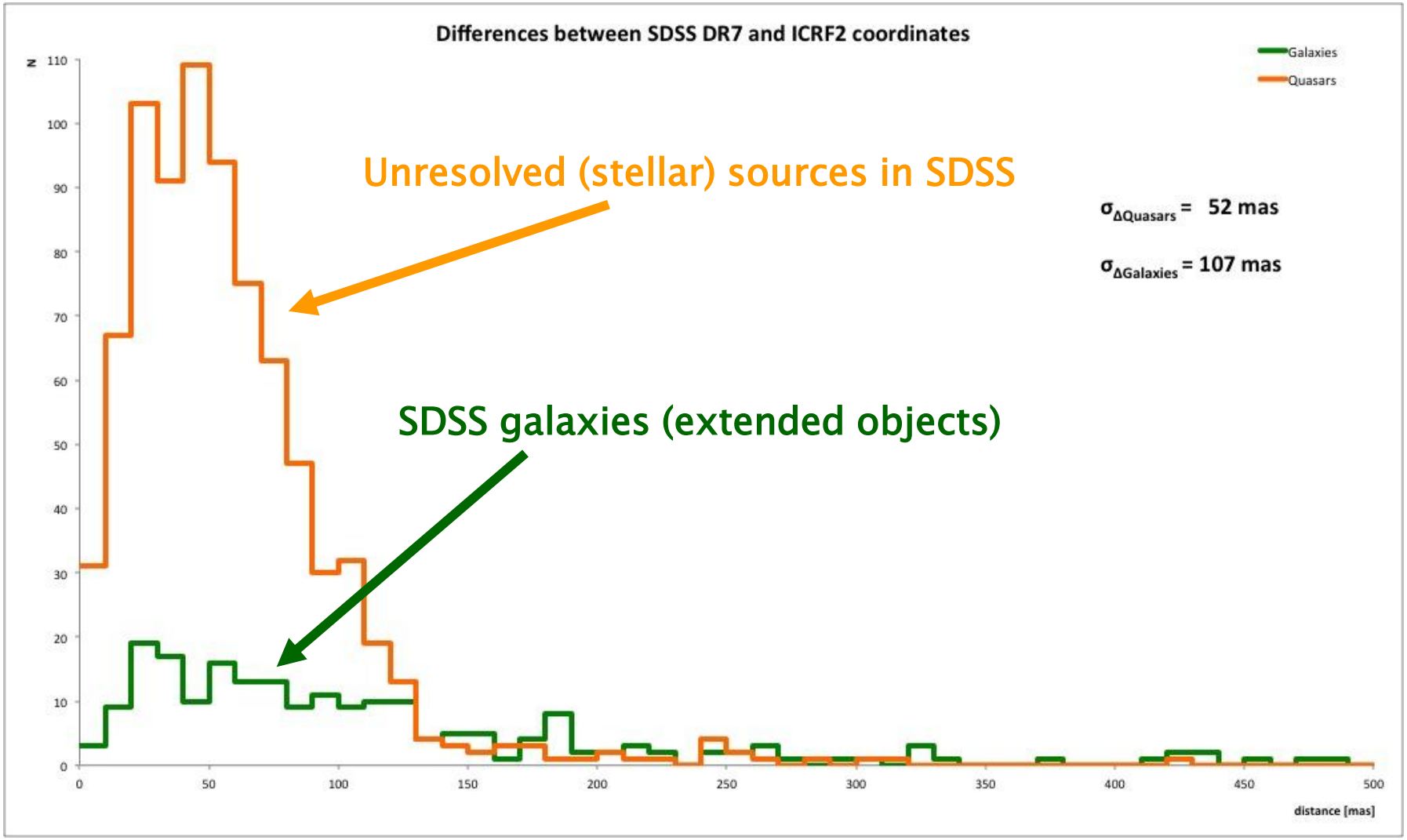
# Common objects on the sky (DR7)



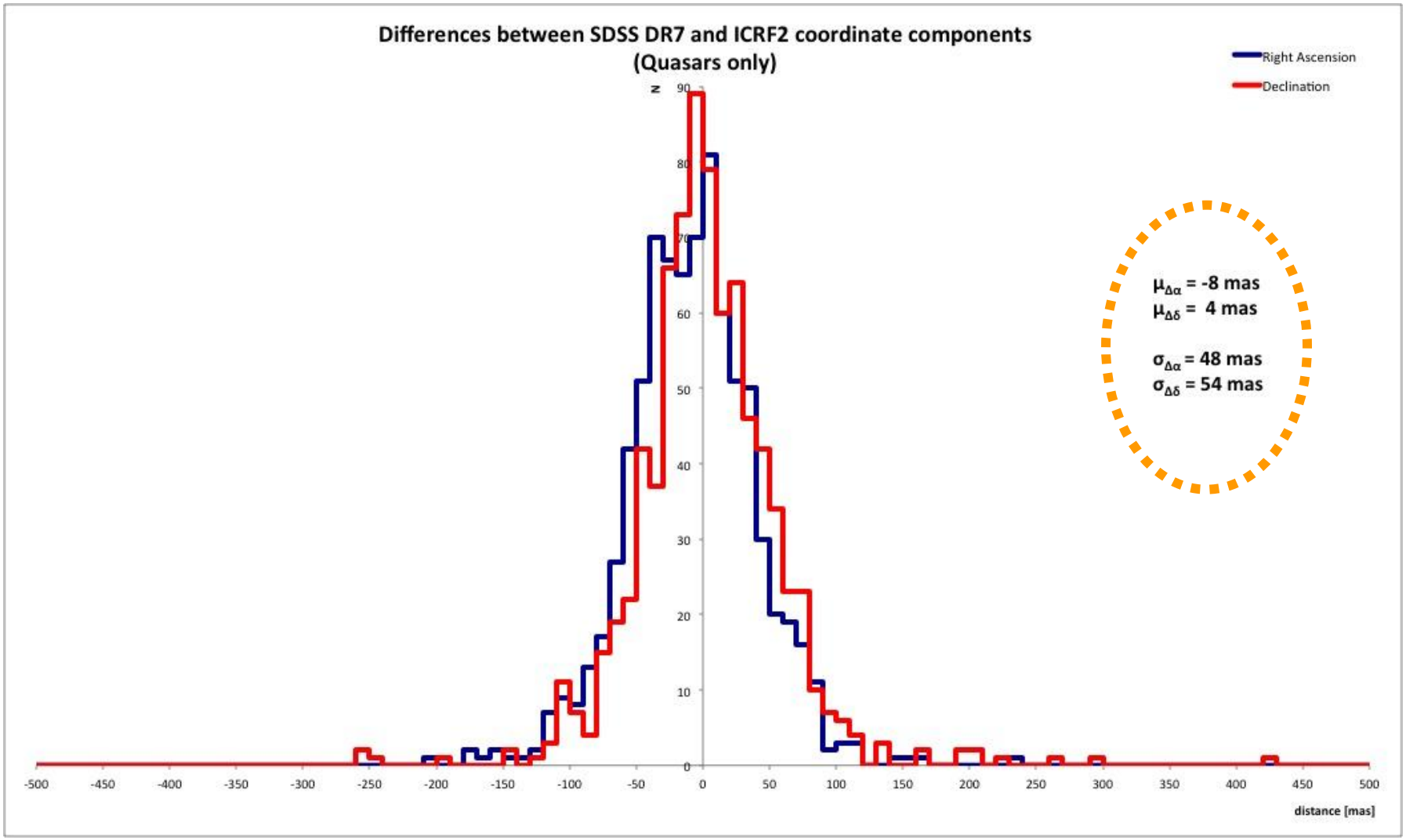
# Common objects on the sky (DR8)

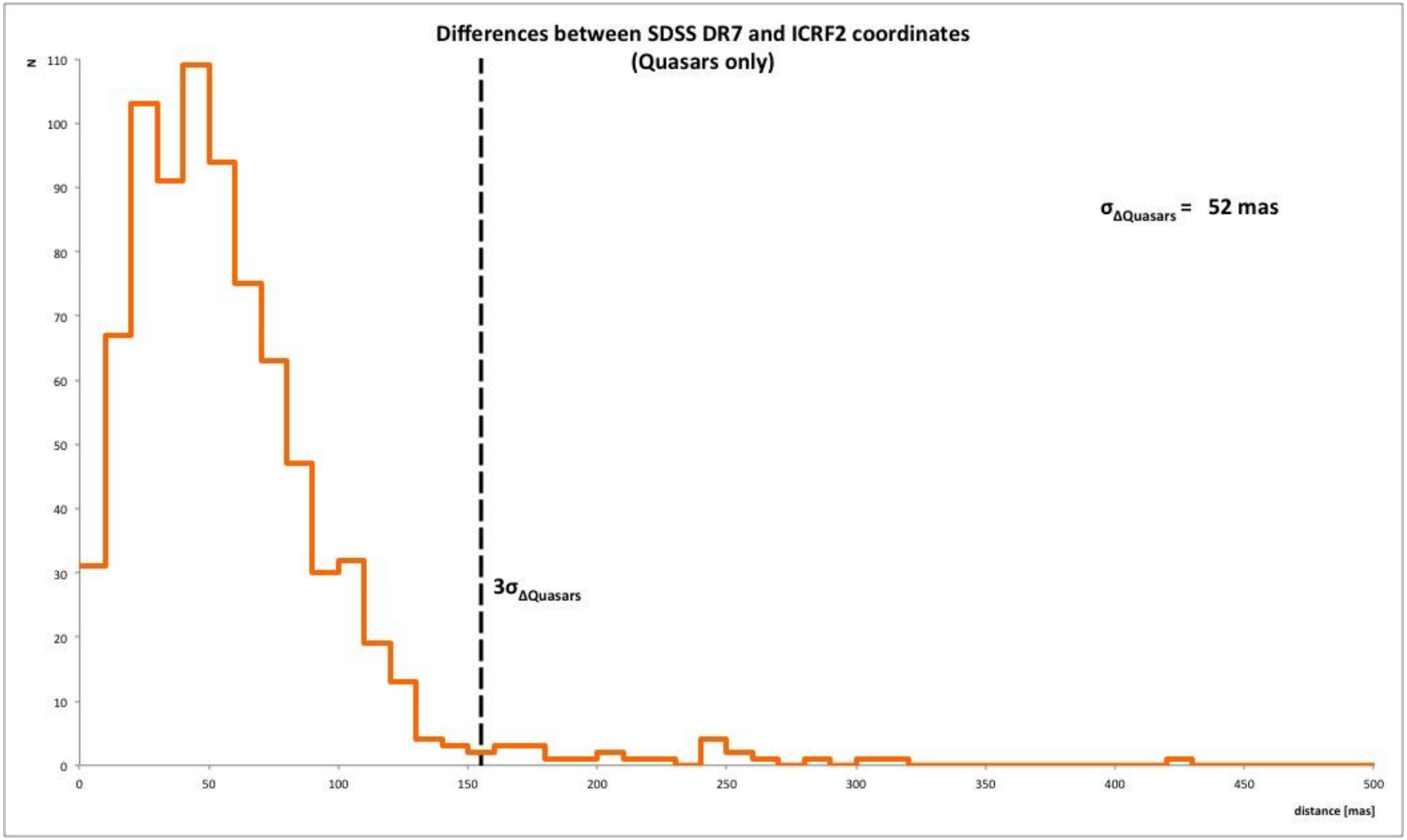


# The distribution of SDSS position offsets

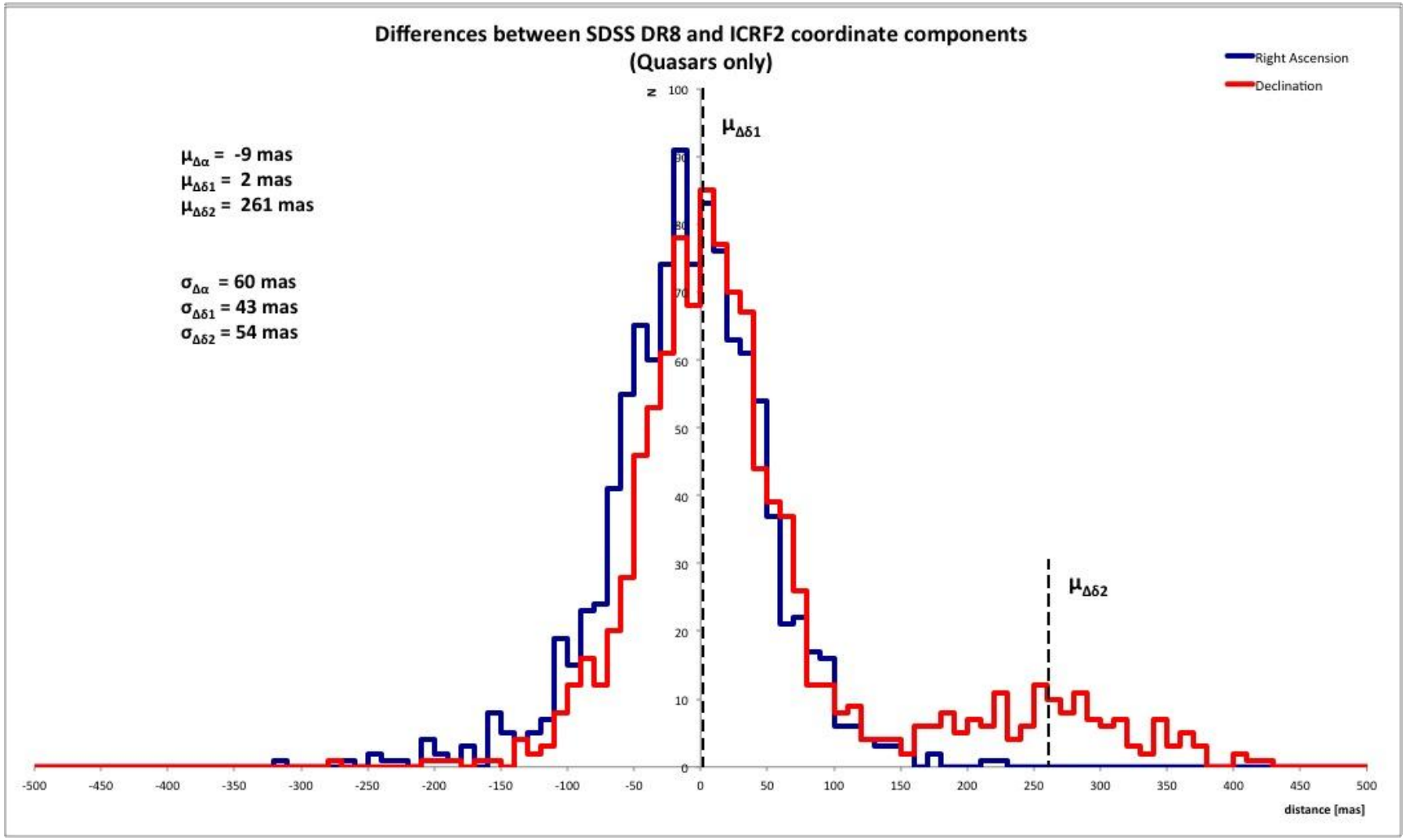


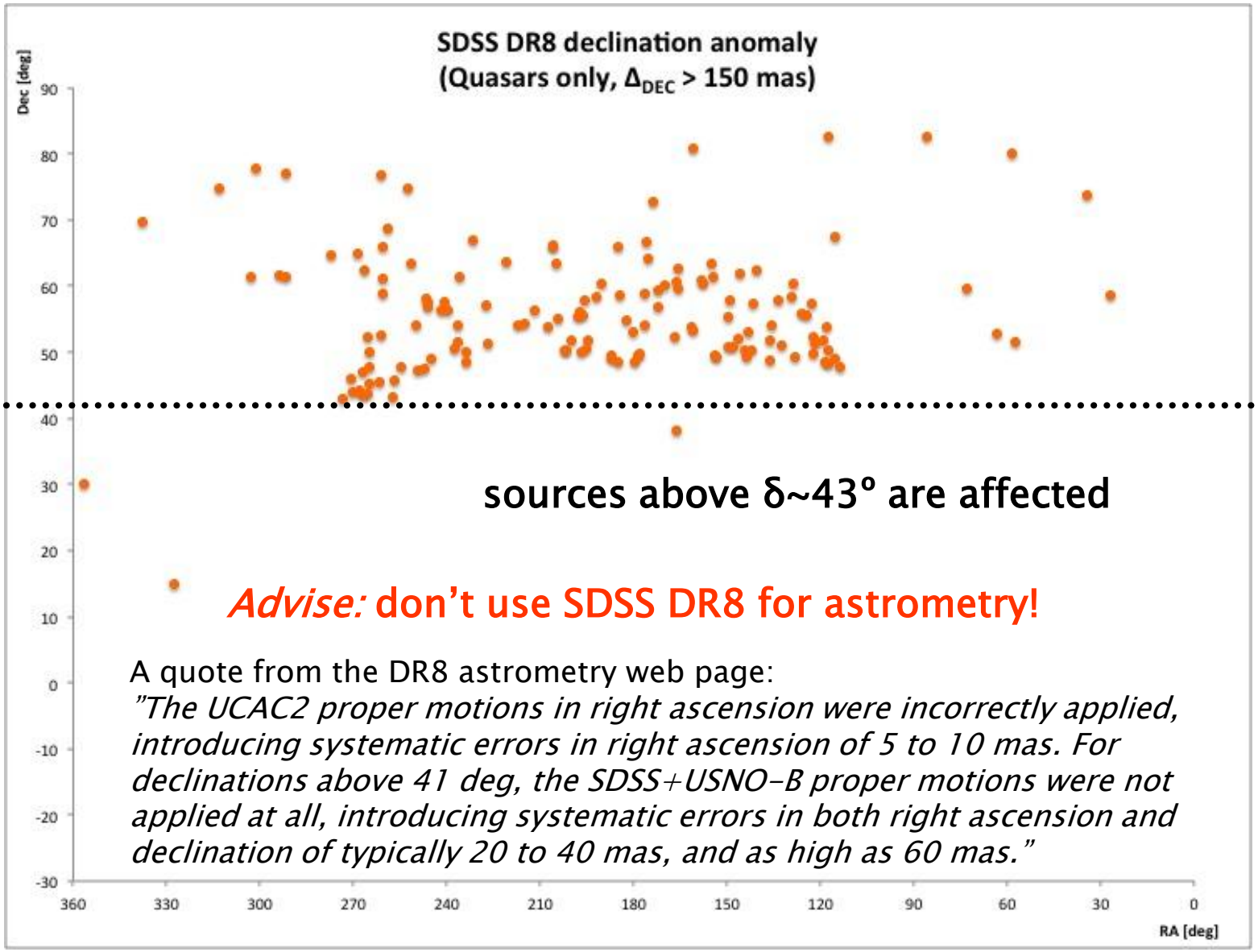

*The stated astrometric accuracy of SDSS DR7 is <100 mas in each coordinate*


Differences between SDSS DR7 and ICRF2 coordinate components
(Quasars only)
Right Ascension
Declination
N
90
80
70
60
50
40
30
20
10
0
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300
350
400
450
500
distance [mas]
$\mu_{\Delta\alpha}$ = -8 mas
$\mu_{\Delta\delta}$ = 4 mas
$\sigma_{\Delta\alpha}$ = 48 mas
$\sigma_{\Delta\delta}$ = 54 mas


Differences between SDSS DR7 and ICRF2 coordinates
(Quasars only)
N
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
distance [mas]
$\sigma_{\Delta Quasars}$ = 52 mas
$3\sigma_{\Delta Quasars}$

# A quick look at DR8...



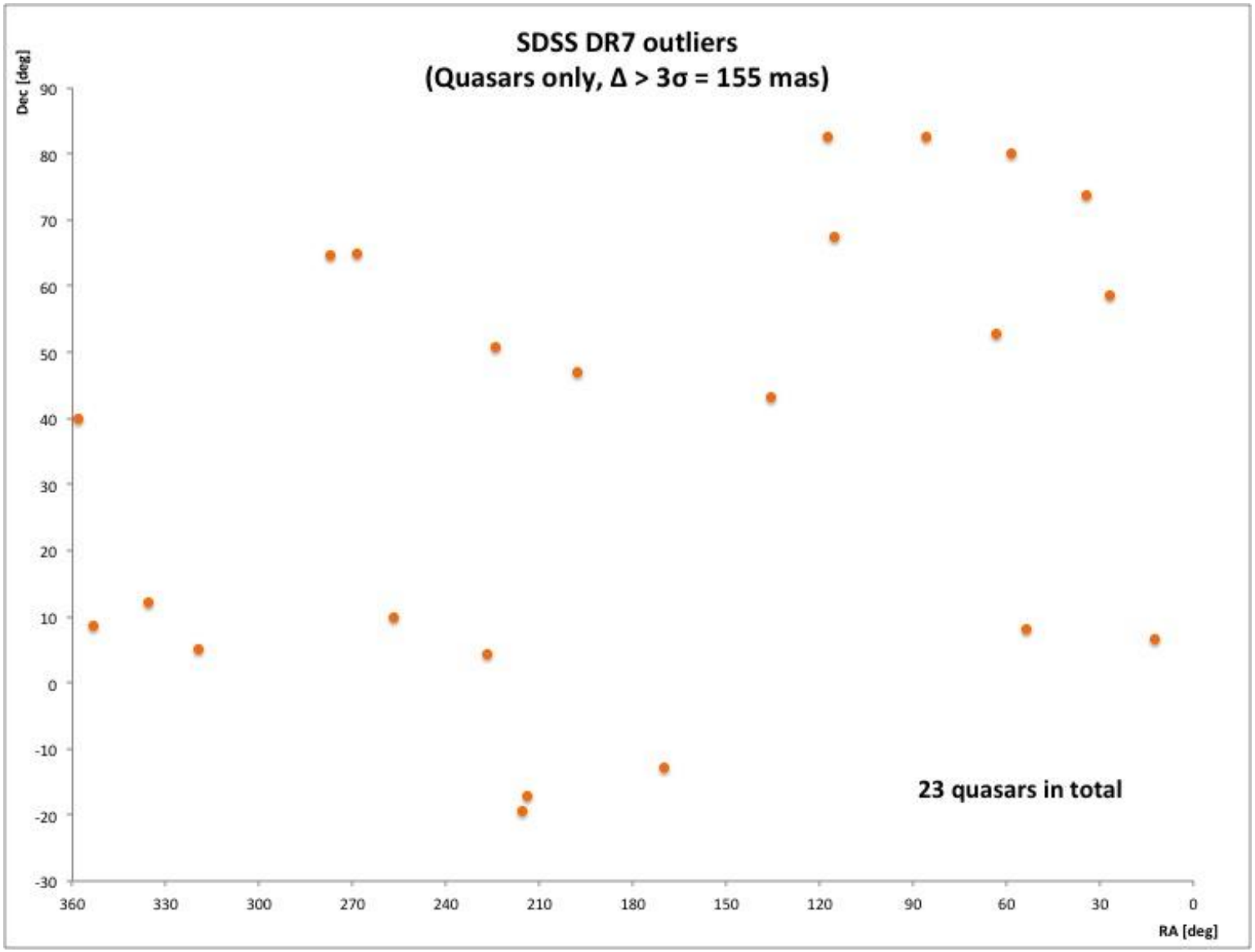



**sources above δ~43° are affected**

***Advise:*** **don't use SDSS DR8 for astrometry!**

A quote from the DR8 astrometry web page:

*"The UCAC2 proper motions in right ascension were incorrectly applied, introducing systematic errors in right ascension of 5 to 10 mas. For declinations above 41 deg, the SDSS+USNO-B proper motions were not applied at all, introducing systematic errors in both right ascension and declination of typically 20 to 40 mas, and as high as 60 mas."*


SDSS DR7 outliers
(Quasars only, Δ > 3σ = 155 mas)
Dec [deg]
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
360
330
300
270
240
210
180
150
120
90
60
30
0
RA [deg]
23 quasars in total

# Outliers in DR7

**There are ~20 SDSS optical quasars with at least 3σ (155 mas) positional offset from the corresponding ICRF2 position**

**Are they chance identifications?**

*Certainly not! Simulations using a large "fake" ICRF catalogue show that the probability of chance coincidence is 0.02% within 300 mas, and 0.05% within 500 mas*
*→ only 1 or 2 unrelated optical sources are expected within our search radius*

**Do they result from astrometric mis-calibration in SDSS?**

*Maybe… This cannot be excluded, at least for some of the sources / SDSS fields. But probably does not explain all outliers.*

# Astrophysical reasons?

**Core shift?**

*Opacity effect (frequency-dependent position of the VLBI "core")*
*~0.1 mas systematic difference between the radio (8 GHz) and optical*
Andrei Lobanov's and Kirill Sokolovsky's talks
e.g. Sokolovsky et al. 2011 (A&A, in press)
Kovalev et al. 2008 (A&A 483, 759)
*--- too small compared to our offsets*

**Extended vs. compact radio sources?**
*Optical-radio position differences in a large sample of radio sources are systematically higher (~8 mas) for extended radio sources*
da Silva Neto et al. 2002 (AJ 124, 612)
*--- too small compared to our offsets*

# Astrophysical reasons? *(cont.)*

## Gravitational lensing?

*The compact radio emission originates from a background source, while the optical is dominated by the lensing foreground galaxy*
Ian Browne's and Francois Finet's talks
*--- how many of them? probably can't explain each outlier*

## Dual AGNs?

*The (projected) linear size corresponding to 150-300 mas angular size at the redshift of e.g. z=1 is ~1.2-2.4 kpc*
*(using the "standard" cosmological model)*
*These correspond to sub-galactic sizes*
*--- mergers with such separations do exist*

*Radio emission from e.g. double-peaked narrow [O III] emission line quasar pairs from SDSS is detected in ~50 cases, although these are generally weak radio sources – unlike ICRF2 objects*
*(Li C. et al. 2011, in prep.)*

# Summary

- There are 1014 ICRF2 radio sources with optical counterparts in SDSS DR7, the majority of them are quasars (i.e. optically unresolved)

- SDSS DR7 quasar positions are accurate to ~50 mas

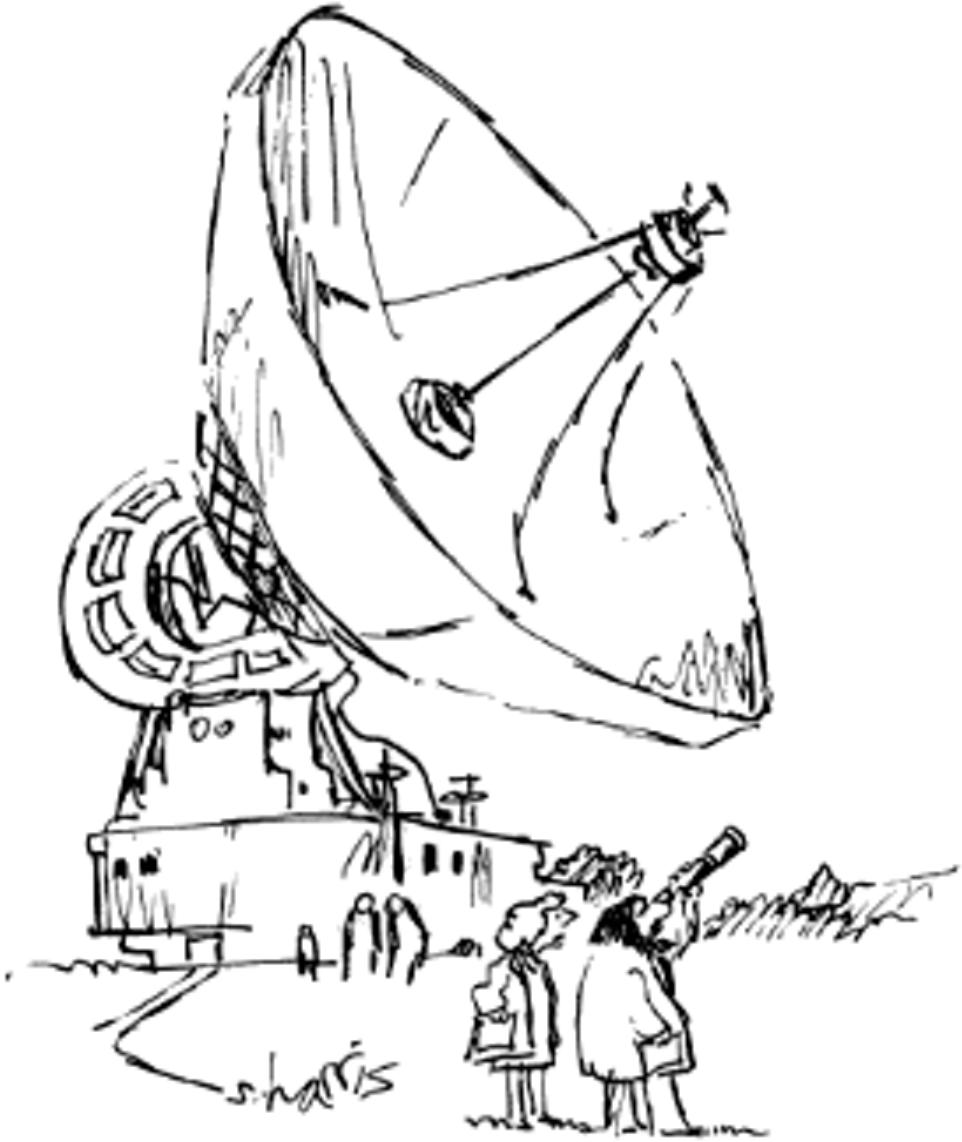
- Don't touch SDSS DR8 if you have astrometry in mind…

- There are over 20 quasars for which the ICRF2 and SDSS positions exceed 155 mas (3σ)

- These should be further investigated to reveal the cause(s) of such large non-coincidences

- When the accurate optical and radio frames are finally aligned, one must filter out such peculiar sources from the link objects *(and study them from astrophysical points of view!)*

# Thank you for your attention!




"Just checking."

*Cartoon:* © Sydney Harris